NASA TECHNICAL MEMORANDUM

NASA TM X-52329

NASA TM X-52329

VAPOR-PRESSURE DATA EXTRAPOLATED TO 1000 ATMOSPHERES FOR 10 REFRACTORY ELEMENTS WITH THERMAL ABSORPTION CROSS SECTIONS LESS THAN 5 BARNS

by Charles C. Masser
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Fourth Symposium on Thermophysical Properties
sponsored by the American Society of Mechanical Engineers
College Park, Maryland, April 1-4, 1968

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1967

VAPOR-PRESSURE DATA EXTRAPOLATED TO 1000 ATMOSPHERES FOR 10 REFRACTORY ELEMENTS WITH THERMAL ABSORPTION CROSS SECTIONS LESS THAN 5 BARNS

by Charles C. Masser

Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at

Fourth Symposium on Thermophysical Properties
sponsored by the American Society of Mechanical Engineers
College Park, Maryland, April 1-4, 1968

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

[redacted]

VAPOR-PRESSURE DATA EXTRAPOLATED TO 1000 ATMOSPHERES FOR 10 REFRACTORY ELEMENTS WITH THERMAL ABSORPTION CROSS SECTIONS LESS THAN 5 BARNS

by Charles C. Masser

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

E-3854

ABSTRACT

Increased interest in high-temperature technology makes knowledge of the vapor pressure of refractory materials more important. We have collected existing vapor-pressure data for 10 elements (C, Ce, Mo, Nb, Pt, Ru, V, W, Y, Zr). These have atmospheric boiling points over 3000° K and thermal absorption cross sections less than 5 barns. Data were discussed and extrapolated to 1000 atmospheres. An error analysis was used to indicate the error in temperature at a given pressure introduced by scatter in the original data. At 1000 atmospheres, zirconium has the highest boiling point (10 100° K).

INTRODUCTION

As interest in high-temperature technology increases, the need for predicting the vapor pressure of materials at these high temperatures and pressures becomes more important. This is of particular interest in nuclear engineering, where the systems usually involve high temperatures and pressures. One group of materials that is in frequent use in nuclear engineering concepts has low vapor pressure and low thermal absorption cross section. This type of material is used in gas-core (ref. 1) and liquid-core (ref. 2) nuclear-rocket

concepts. In these concepts, hydrogen propellant is radiantly heated by a nuclear fuel. However, hydrogen gas at a temperature less than 5000° K cannot absorb radiant heat because of its transparency. A powdered material can be suspended in the hydrogen propellant to absorb the radiant heat leaving the reacting fuel and then to conduct the heat to the hydrogen propellant. If it is assumed that only the particle absorbs radiant heat, a low-vapor-pressure material is necessary to keep the vaporization rate low. Therefore, in this report, only elements which have atmospheric boiling points over 3000° K were selected. The material must also have a low thermal absorption cross section in order not to cause an increase in the critical mass of the system. Therefore a maximum of 5 barns was placed on selecting elements. References 3 and 4 contain summaries of vapor-pressure data for the elements with estimated atmospheric boiling points, and reference 5 contains the values of thermal absorption cross sections.

This study was performed to collect, evaluate and select the best vapor-pressure data available, and then to extrapolate them to 1000 atmospheres. The 10 elements chosen were C, Ce, Mo, Nb, Pt, Ru, V, W, Y, and Zr. Their values of thermal absorption cross section, and the references from which the vapor-pressure data were taken are shown in table I.

COLLECTION AND EVALUATION OF VAPOR-PRESSURE DATA

Examination of the available data indicate that most experimental data were obtained at temperatures less than 3000° K and that, hence,

the vapor pressures were in the range of 10^{-5} to 10^{-10} atmospheres. Therefore, an extrapolation of at least 7 orders of magnitude is required to reach the desired 1000 atmospheres.

During the collection and evaluation of vapor-pressure data, it was necessary to judge the reliability of reported vapor-pressure measurements. In the cases where more than one set of vapor-pressure data are collected for a given material, each is discussed. If one set is preferred over the other, the reasons are discussed and only the preferred set is retained; otherwise all sets are retained. The following factors were considered:

(1) The behavior of the system

(2) The identification of the various gaseous species in the system

(3) The experimental technique by which the vapor pressure was measured

(4) The range and scatter of the vapor-pressure data

The investigation of the general behavior of the system should reveal whether there is any reaction between the sample and any other part of the system. If there is a reaction, the resulting phase may vaporize and affect the vapor-pressure measurements. Or the reaction may contaminate the sample by changing the samples composition. The measured vapor pressure thus would not be of the pure sample but of the contaminated one.

The various gaseous species must be identified to complete any vapor-pressure experiment. Several different species may vaporize from a sample, and each must be identified and its share of the vapor pressure calculated or measured. Whenever vapor-pressure data are

extrapolated, the vapor pressure of each individual species should be extrapolated, rather than the sum of the partial pressures of the species.

Vapor-pressure measurements on high-temperature materials are suitably made by using either the Knudsen or the Langmuir method. Both methods require a high-vacuum system. In the Knudsen method, the sample is contained in an inert crucible that has a small, thin orifice. This container is called a Knudsen cell. Equilibrium is established inside the crucible if the orifice is sufficiently small. However, all the vapor striking the orifice inlet does not leave the orifice outlet. The ratio between the rate at which vapor leaves the orifice outlet and that at which vapor strikes the orifice inlet is given by a "Clausing factor." This Clausing factor is governed only by the dimensions of the orifice. The rate of effusion through the orifice is then governed by the Clausing factor, the temperature, the molecular weight of the effusing vapor species, and the vapor pressure.

In the Langmuir method, no crucible is used but rather free evaporation occurs from the entire sample surface. The vapor pressure is therefore a function of the rate at which material sublimes from the sample, the surface area and the absolute temperature of the sample, and the molecular weight of the vapor leaving the sample.

METHOD OF EXTRAPOLATION

The curve that was fitted to the data and extrapolated to 1000 atmospheres can be derived from the Clapeyron equation for a constant heat of vaporization and is of the form

$$\log P = \frac{A}{T} + D \qquad (1)$$

where A and D are constants, P is vapor pressure in atmospheres, and T is temperature in ^{o}K.

We used least-squares method to fit the selected vapor-pressure data to equation (1). In the majority of cases, the referenced literature already reported the results using this method with equation (1). However, the data were refitted to equation (1) using the least-squares method.

The possible error in predicting a value of vapor pressure from extrapolated data originates from three sources. First, there is the error introduced by the assumption of constant heat of vaporization which results in equation (1). The importance of this error cannot be assessed until additional experimental data at higher temperatures become available Second, a systemic error may already be present in the original vapor-pressure data. Assessment of the magnitude of this type of error is also not possible. Third, there is an error caused by the random scatter of the data. This error can be estimated.

Figure 1 shows a schematic drawing of the error analysis used by us to estimate the third type of error. By using the common logarithmic coordinate of vapor pressure and reciprocal temperature,

equations in the form of equation (1) are represented by straight lines. In figure 1, the lines W and X are visually drawn parallel and equidistant from the line generated when curve fitting the data to equation (1). These boundary lines encompass at least 90 percent of the data points. The diverging lines, Y and Z, encompass all possible straight lines that can be drawn through the data. These two straight lines are then extended to a pressure of 1000 atmospheres. The "temperature uncertainty" is the difference at a given vapor pressure between the temperature value given by equation (1) and the values given by the two diverging lines, Y and Z. The calculated temperature uncertainty is for a given set of vapor-pressure data and reflects only the random error caused by the scatter in the data. Figure 1 shows that the magnitude of the temperature uncertainty at a given pressure is also dependent on the amount of extrapolation from the original data. Where two or more sets of data are selected, each is extrapolated to 1000 atmospheres. The results are then combined: the average value of A and D are found and these average values are used in the extrapolation. Also the temperature uncertainty at a given pressure includes the entire range found for all sets of data.

DISCUSSION OF MATERIALS

Carbon

In reference 6 mass spectrographic studies were performed on carbon in the temperature range from 1800° to 2700° K. The ions observed were C_1^+, C_2^+, C_3^+, C_4^+, and C_5^+; the intensities of C_6^+/C_1^+ and C_7^+/C_1^+ were less than 5×10^{-4} at 2500° K, and no results were

reported for the two species C_6 and C_7. To minimize temperature uncertainties ref. 6 assumed the vapor pressure of C_1 to be known and its associated value for the heat of vaporization ΔH_o^o to be equal to 169.58 kilocalories per gram atom. A least-squares treatment was applied to the relative intensities C_n^+/C_1 to calculate $\Delta H_o^o(C_n)$ where $n \leq 5$. The ratios were divided by 2.30, 3.66, 4.96, and 6.30 for C_2 to C_5, respectively, to convert to relative pressures. We used a trial and error graphical method to calculate the temperature of the total carbon vapor pressure at 1 to 1000 atmospheres. The partial pressure of C_1 to C_5 were summed and table II(a) gives temperatures for total carbon pressures of 1, 10, 100, and 1000 atmospheres. The errors involved in C_2 to C_5 are based on a given value of C_1; therefore, any error in C_1 increases the errors of the larger carbon polymers. In addition, carbon polymers larger than C_5 start to influence the total vapor pressure in this pressure range.

Reference 7 describes a mass spectrometric study of the vapor ejected from a graphite sample that was flash heated by a focused laser beam. The relative abundance of the carbon polymer species, C_1 to C_{11} and C_{14}, at approximately 4000^o K was obtained. The relative ion intensities of the various carbon species did not vary significantly for different graphite samples; however, a standard deviation of about 50 percent necessitated a large number of measurements on each carbon species. A typical averaged mass spectrum is presented in reference 7, with the extrapolated results of reference 6, and is reproduced in table II(b). The agreement between Drowart, et al, (ref. 6) and Berkowitz, et al, (ref. 7) is good considering the

differences in the methods used. It is also interesting that, from the data of reference 7, the carbon species C_7 approaches the magnitude of C_4 and C_5 in importance and that at higher pressures and temperatures it may become dominant.

Cerium

The vapor-pressure data for liquid cerium were obtained directly from Habermann, et al (ref. 8), and consist of 19 data points in the temperature range from 1861° to 2252° K. The Knudsen technique was used involving a quartz-fiber microbalance. The cerium was 99.9 percent pure. The major impurities detected were tantalum, 100 parts per million (ppm); iron, 250 ppm; oxygen, 345 ppm; carbon, 200 ppm; nitrogen, 150 ppm; and traces of calcium, silicon, fluorine, and hydrogen, 95 ppm. Table II(c) indicates the results when the vapor-pressure data were extrapolated to 1000 atmospheres.

Molybdenum

Three references were used for the extrapolated vapor pressure of solid molybdenum. Edwards, et al (ref. 9) used the Langmuir method; nine data points were recorded in the temperature range from 2151° to 2462° K. The sample was at least 99.957 percent molybdenum. Spectroscopic analysis showed the presence of 0.023 percent carbon and 0.01 to 0.001 percent each of iron and silicon. In table II(d), extrapolation of the data of reference 9 to 1000 atmospheres is presented.

Vozzella, et al. (ref. 10) also used the Langmuir method for solid molybdenum. An automatic recording semimicro vacuum balance and a calibrated optical pyrometer were used to obtain measurements

in the temperature range from 2141° to 2533° K; 12 data points are presented. The sample showed 99.89 percent molybdenum. Impurities amounted to 1730 ppm; oxygen, 30 ppm; carbon, 700 ppm; and traces of iron, nickel, chromium, and silicon, totaling 1000 ppm. An extrapolation of the data to 1000 atmospheres yielded the results shown in table II(e).

Fries (ref. 11) also used the Langmuir method for solid molybdenum. The apparatus used by Fries (ref. 11) was essentially the same as that used by Vozzella, et al., (ref. 10). Twelve data points were recorded in the temperature range from 2086° to 2489° K using an optical pyrometer. Maximum impurities amounting to 1085 ppm consisting of oxygen, 45 ppm; nitrogen, 20 ppm; niobium, tungsten and zinc, each 150 ppm; iron, 75 ppm; tantalum, zirconium, strontium, colbalt, titanium, potassium, and silicon, each 45 ppm; and trace materials amounting to 180 ppm. Extrapolating the data to 1000 atmospheres yielded the results shown in table II(f).

Because each set of data (refs. 9, 10, and 11) yields different results for the vapor pressure at 1 to 1000 atmospheres all three sets were combined. The results of this procedure are listed in table II(g), along with the temperature uncertainty which was calculated using all three sets of data.

Niobium

Two sets of data for the vapor pressure of solid niobium are discussed herein. The first set (ref. 12) was presented in 1959. The Langmuir method was employed, and temperatures were measured by sighting with an optical pyrometer into a blackbody hole drilled into

the sample. Seventeen data points were recorded in the temperature range from 2304° to 2596° K. The sample purity was 99.9 percent, but no mention was made of the types of impurities; however, the sample was thoroughly outgassed before it was heated inductively and measurements taken. In table II(h) the data of reference 12 are extrapolated to 1000 atmospheres.

In 1962 the Langmuir method was again used (ref. 13), the temperatures were measured with an optical pyrometer, which was sighted on a blackbody hole drilled in the sample. The experimenter used a high-temperature thermobalance which incorporated a new furnace design that gave stable temperatures up to 3000° K. Impurities amounted to 248 parts per million; carbon, 20 ppm;, oxygen, 100 ppm; nitrogen, 8 ppm; hydrogen, 5 ppm; tantalum, 100 ppm; iron, 8 ppm; and silicon, 7 ppm. The raw vapor-pressure data were received from Woerner, et al. (ref. 13), and consisted of 32 data points in the temperature range from 2241° to 2588° K. The data were extrapolated to 1000 atmospheres and the results are shown in table II(i).

Each set of data (refs. 12 and 13) is essentially in the same temperature range, and the resulting vapor-pressure lines are parallel. This indicates that the experimenters are in agreement on the slope of the vapor-pressure curve but that a systemic error in the temperature or weight measurements caused a shift in the vapor pressure values. The difference in the two curves on the temperature scale is 40° K. When the results are averaged a vapor-pressure line

parallel to and between the two sets of data is formed and these results are shown in table II(j).

Platinum

The first set of platinum data discussed herein is presented in reference 14. The Langmuir technique was used, and the vapor pressure of solid platinum was measured in the temperature range from 1571° to 1783° K. The sample was at least 99.95 percent pure, but no mention was made of the types of impurities. Only nine data points are presented and five of these are within 5° K of 1740° K; therefore, it was difficult to estimate an error throughout the temperature range investigated. The vapor-pressure curve calculated from the data of reference 14 resulted in an equation that was of the same form but numerically different from that calculated in reference 14. At 1000 atmospheres, equation (1) gives a temperature of 5430° K whereas the equation calculated in reference 14 predicts 6490° K. Because Dreger, et al. (ref. 14) may not have used the least-squares method for calculating the vapor-pressure equation, or because other unmentioned factors may have entered his calculations, these data were not used for extrapolation purposes.

A second set of platinum vapor-pressure data is presented in reference 15. A microbalance was used in measuring the vapor pressure of solid platinum by the Langmuir technique over the range from 1916° to 2042° K. A plot of the 18 data points shows a good distribution over the temperature range (Hampson, et al. (ref. 15)), but because the temperature range was only 125° K, the temperature uncertainty becomes large at 1000 atmospheres. The platinum sample

was approximately 99.7 percent pure. The major impurities were palladium, iridium, and rhodium at percentage levels of 0.01 to 0.1 percent, copper and iron at percentage levels of 0.001 to 0.01 and silver at less than 0.001 percent. An extrapolation to 1000 atmospheres results in temperature estimates shown in table II(k).

Ruthenium

Survey studies were made of three references containing information on the vapor pressure of solid ruthenium. In reference 16, 24 data points for ruthenium in the temperature range from 2036° to 2591° K are presented. Sixteen data points were obtained by the Knudsen method; the other eight points were obtained by the Langmuir technique. The Knudsen method employed ruthenium 103 as a radioactive tracer in the vaporizing ruthenium metal. The radioactivity of the target on which the effusion beam condensed was then compared with a previously calibrated sample.

The Langmuir evaporation studies by Panish, et al. (ref. 16) were performed on a small cylindrically shaped pellet of ruthenium containing a blackbody hole for temperature measurements. Trace amounts of impurities were found spectroscopically; however, the types and amounts were not reported. By extrapolating the data to 1000 atmospheres, results for the vapor pressure of ruthenium were calculated and are shown in table II(l).

Reference 17 presents studies of the vapor pressure of solid ruthenium in the temperature range 2011° to 2330° K. By using the Langmuir technique in conjunction with a microbalance built inside the vacuum system, nine data points were obtained. The sample

was between 99. 8 and 99. 98 percent ruthenium, with the major impurities being platinum and calcium from 0. 01 to 0. 1 percent. Extrapolation of these nine data points yields the values given in table II(m).

Reference 18, reports the vapor pressure of solid ruthenium in the temperature range from 1918° to 2377° K, using the Langmuir method. A microbalance was used for weight measurements, and a calibrated pyrometer was used for temperature measurements. Two samples of different purities were used. Sample 1 had a purity greater than 99. 97 percent, with the major impurities being less than 0. 02 percent osmium and less than 0. 007 percent rhodium. Sample 2 had a purity greater than 99. 8 percent, with the major impurities being less than 0. 1 percent platinum and calcium. In reference 18, 42 data runs were presented using sample 1, and 52 runs were presented using sample 2. Extrapolating the data to 1000 atmospheres results in the vapor-pressure values presented in table II(n).

The resulting vapor-pressure equations of references 16 to 18 were averaged and extrapolated to 1000 atmospheres. These results are presented in table II(o).

Tungsten

The vapor pressure of solid tungsten is reported in reference 19, where 10 data points are recorded in the temperature range from 2574° to 3183° K. The Langmuir method was used with the aid of a vacuum microbalance. A calibrated optical pyrometer was used to

measure temperatures by sighting on a blackbody hole drilled in the specimen. Results of a spectrochemical analysis indicate a maximum impurity content of 0.02 percent where molybdenum and silicon are the principal impurities. The results obtained by extrapolating these data to 1000 atmospheres are shown in table II(p).

Vanadium

The vapor pressure of solid vanadium was measured in the temperature range from 1666° to 1882° K in reference 20 by the Langmuir method. The vanadium sample was heated inductively and temperature measurements were made with an optical pyrometer that was sighted on a blackbody hole drilled in the sample. The sample contained 99.6 percent vanadium, 0.2 percent carbon, 0.1 percent hydrogen, with traces of iron, silicon, manganese, copper, and calcium comprising the other 0.1 percent. No correction factor was applied to the vapor-pressure measurements resulting from these impurities. However, in several of the initial runs, gas was evolving from the sample which would indicate outgassing of some impurities, and these runs were rejected; 12 data points were recorded. The results are presented in table II(q) for the extrapolation of the data to 1000 atmospheres.

Yttrium

The vapor pressures of liquid yttrium from two references are discussed and compared herein. Reference 21 contains data on liquid yttrium in the temperature range from 1774° to 2103° K. An inductively heated, tungsten Knudsen cell was used, and weight measurements were made with a vacuum balance, while temperatures were

recorded by an optical pyrometer. Seven vaporization data points were recorded from the sample of yttrium, which contained about 0.4 percent calcium. However, the orifice of the Knudsen cell was not thin, and a Clausing factor of 0.36 was used in the calculations.

Reference 8 presents a vapor-pressure study of liquid yttrium. The Knudsen method was used in conjunction with a quartz-fiber microbalance for weight measurements, and an optical pyrometer for temperature measurements. Data for 18 runs were received from Habermann, et al. (ref. 8); and were in the temperature range from 1861° to 2252° K. The sample was better than 99.98 percent yttrium. The impurities were tantalum, 400 ppm; iron, 150 ppm; oxygen, 300 ppm; carbon, 150 ppm; fluorine, 100 ppm; and 65 ppm of trace materials.

In extrapolating the vapor-pressure data, only the data of reference 8 were used. The advantages of this set of data were the following. First, the orifice in the Knudsen cell was much thinner than that used in reference 21. This led to a Clausing factor of 0.9666 compared with 0.36 in reference 21. Second, 18 data points were received from Habermann, et al. (ref. 8) compared with 7 presented in reference 21. Table II(r) shows the results or extrapolating the data of reference 8 to 1000 atmospheres.

Zirconium

Data on the vapor pressure of zirconium were obtained from three references. The first set of data is presented by Skinner, et al. (ref. 22) in 1951. The vapor pressure of solid zirconium was measured between 1949° and 2054° K by the Langmuir technique.

The zirconium sample was heated inductively while temperature measurements were taken from optical pyrometer readings. Weight loses were determined by two methods: first, by collecting and analyzing the evaporated film and, second, by direct measurement of the sample weight loss.

The zirconium sample contained 0.99 atom percent hafnium, 0.05 atom percent tungsten, and 0.37 atom percent of other impurities, which were mostly silicon and aluminum. A plot of the data shows a good distribution over the temperature range, however, this data was not used for extrapolation purposes. The reason for this is the availability of more recent vapor-pressure data on liquid zirconium.

The second set of data was presented by Federov et al. (ref. 23) in 1962. The vapor pressure of solid zirconium measured using the Knudsen method with radioactive indicators. Data was obtained from two Knudsen cells with different diameter openings. Six data points from a cell with an effusion apertures diameter of 1.4 millimeters and four data points from a cell having a 0.99 millimeter effusion aperture. The Knudsen cell was made of molybdenum and was resistance heated by passing current through tungsten wires. Temperature measurements were made with thermocouples in the range from 1540° to 1680° K and weight measurements were made on a target where the evaporated metal condensed. Again this vapor-pressure data was not used because the zirconium was in a solid state.

The third set of data presented by Trulson et al. (ref. 24) in 1965 contains vapor pressure data of both solid and liquid zirconium. A mass spectrometer was used with a Knudsen cell to obtain fourteen data points on solid zirconium (1968° to 2112° K) and eight data points on liquid zirconium (2148° to 2274° K). Temperature measurements were made with an optical pyrometer sighted into blackbody holes drilled in the crucible wall. The zirconium measurements were made in a graphite crucible lined with zirconium carbide, however, no mention was made on the area of the Knudsen effusion aperture. The solid and liquid vapor pressure data were separately fitted to equation 1 and there is a marked difference in slope of the vapor pressure line caused by the heat of fusion. Since we are interested in extrapolating the data to 1000 atmospheres only the eight liquid data points are used. Since the liquid temperature range is only 126° K a large temperature uncertainty is calculated at 1000 temperatures. Table II(s) summarizes the extrapolation of the least-squares curve fit and the temperature uncertainty.

CONCLUDING REMARKS

Existing vapor-pressure data were collected from the literature for 10 elements. The materials chosen had a thermal neutron absorption cross section less than 5 barns and an atmospheric boiling point over 3000° K. Each set of data was curve fitted to an equation of the following form:

$$\log P = \frac{A}{T} + D$$

where A and D are constants, P is vapor pressure, and T is

temperature. The constants A and D were obtained for each of the materials discussed herein and are listed in table III.

Equation (1) was used to extrapolate the vapor-pressure data to 1000 atmospheres. Whatever limitations exist in using the preceding for extrapolating vapor-pressure data exist in the extrapolations presented herein. An error analysis was used to find the possible error in the extrapolated vapor pressure due to the scatter of the original data. Figure 2 plots the extrapolated vapor pressures for all of the elements chosen from 1 to 1000 atmospheres. At 1000 atmospheres, zirconium has the highest boiling point (10 100° K).

REFERENCES

1. Rom, Frank E.; and Ragsdale, Robert G.: Advanced Concepts for Nuclear Rocket Propulsion. Nuclear Rocket Propulsion. NASA SP-20, pp. 3-15.
2. Ragsdale, Robert G.; Kascak, Albert F.; and Donovan, Leo F.: Heat- and Mass-Transfer Characteristics of an Axial-Flow Liquid-Core Nuclear Rocket Employing Radiation Heat Transfer. NASA TN D-4127, 1967.
3. Honig, Richard E.: Vapor Pressure Data for the Solid and Liquid Elements. RCA Rev., vol. 23, no. 4, Dec. 1962, pp. 567-586.
4. Nesmeianov, Andrei N. (J. I. Carasso, trans.): Vapor Pressure of the Element. Academic Press, 1963.
5. Weast, Robert C., ed.: Handbook of Chemistry and Physics. Forty-fifth ed., Chemical Rubber Co., 1964.

6. Drowart, J.; Burns, R. P.; DeMaria, G.; and Inghram, Mark G.: Mass Spectrometric Study of Carbon Vapor. J. Chem. Phys., vol. 31, no. 4, Oct. 1959, pp. 1131-1132.

7. Berkowitz, J.; and Chupka, W. A.: Mass Spectrometric Study of Vapor Ejected from Graphite and Other Solids by Focused Laser Beams. J. Chem. Phys., vol. 40, no. 9, May 1, 1964, pp. 2735-2736.

8. Habermann, C. E.; and Daane, A. H.: Vapor Pressures of the Rare-Earth Metals. J. Chem Phys., vol. 41, no. 9, Nov. 1, 1964, pp. 2818-2827.

9. Edwards, James W.; Johnston, Herrick L.; and Blackburn, Paul E.: Vapor Pressures of Inorganic Substances. VIII. Molybdenum between 2151° and 2462° K. Am. Chem. Soc. J., vol. 74, no. 6, Mar. 20, 1952, pp. 1539-1540.

10. Vozzella, P. A.; Miller, A. D.; and DeCrescente, M. A.: Vapor Pressure of Molybdenum. J. Chem. Phys., vol. 41, no. 2, July 15, 1964, pp. 589-590.

11. Fries, R. Jay: An Ultra-High Vacuum Thermobalance for Langmuir Vaporization Studies; Vapor Pressure of Molybdenum. Rep. No. LA-3423, Los Alamos Scientific Lab., Jan. 24, 1966.

12. Speiser, Rudolph; Blackburn, P.; and Johnston, H. L.: Vapor Pressure of Niobium. Electrochem. Soc. J., vol. 106, no. 1, Jan. 1959, pp. 52-53.

13. Woerner, P. F.; and Wakefield, G. F.: High Temperature Thermobalance. Rev. Sci. Instr., vol. 33, no. 12, Dec. 1962, pp. 1456-1457.

14. Dreger, Lloyd H.; and Margrave, John L.: Vapor Pressures of Platinum Metals. I. Palladium and Platinum. J. Phys. Chem., vol. 64, no. 9, Sept. 1960, pp. 1323-1324.

15. Hampson, R. F., Jr.; and Walker, R. F.: Vapor Pressures of Platinum, Iridium, and Rhodium. J. Research, NBS, Sec. A, Phys. and Chem., vol. 65A, no. 4, July-Aug. 1961, pp. 289-295.

16. Panish, Morton B.; and Reif, Liane: Vaporization of Ruthenium and Osmium. J. Chem. Phys., vol. 37, no. 1, July 1, 1962, pp. 128-131.

17. Paule, Robert C.; and Margrave, John L.: Vapor Pressures of Platinum Metals. III. Iridium and Ruthenium. J. Phys Chem., vol. 67, no. 9, Sept. 1963, pp. 1896-1897.

18. Carrera, N. J.; Walker, R. F.; and Plante, E. R.: Vapor Pressures of Ruthenium and Osmium. J. Research, NBS, Sec. A, Phys. and Chem., vol. 68A, no. 3, May-June 1964, pp. 325-330.

19. Szwarc, R.; Plante, E. R.; and Diamond, J. J.: Vapor Pressure and Heat of Sublimation of Tungsten. J. Research, NBS, Sec. A, Phys. and Chem., vol. 69A, no. 5, Sept.-Oct. 1965, pp. 417-421.

20. Edwards, James W.; Johnston, Herrick L.; and Blackburn, Paul E.: The Vapor Pressures of Inorganic Substances. VI. Vanadium Between 1666° K and 1882° K. Am. Chem. Soc. J., vol. 73, no. 10, Oct. 1951, pp. 4727-4729.

21. Ackermann, R. J.; and Rauh, E. G.: Vapor Pressures of Scandium, Yttrium, and Lanthanum. J. Chem. Phys., vol. 36, no. 2, Jan. 15, 1962, pp. 448-452.

22. Skinner, Gordon B.; Edwards, James W.; and Johnston, Herrick L.: The Vapor Pressure of Inorganic Substances. V. Zirconium Between 1949° and 2054° K. Am. Chem. Soc. J., vol. 73, no. 1, Jan. 1951, pp. 174-176.

23. Federov, G. B.; and Smilnov, E. A.: Thermodynamic Properties of Zirconium and its Alloys with Tin. AEC-tr-5551. Translated from paper No. SM-26/57 presented at the Symposium on Thermodynamics of Nuclear Materials, Vienna, May 21-25, 1962.

24. Trulson, O. C ; and Goldstein, H. W.: Mass Spectrometric Study of Zirconium Diboride. J. Physical Chemistry, vol. 69, no. 8, Aug. 1965, pp. 2531-2336.

TABLE I. - REFRACTORY MATERIALS

INVESTIGATED

Material	Thermal absorption cross section, (barns)	Vapor-pressure reference
Carbon	0.00373	6
Cerium	.73	8
Molybdenum	2.70	9, 10, 11
Niobium	1.16	12, 13
Platinum 196	.70	14, 15
Platinum 194	1.2	14, 15
Ruthenium	2.56	16, 17, 18
Tungsten 184	2.0	19
Vanadium	5.0	20
Yttrium	1.31	8, 21
Zirconium	.185	22, 23, 24

TABLE II. - EXTRAPOLATED VAPOR-PRESSURE DATA

(a) Data for carbon from reference 6

Partial vapor pressures of carbon					Total vapor pressure, atm	Extrapolated temperature, ^{o}K	Temperature uncertainty, ^{o}K
C_1, atm	C_2, atm	C_3, atm	C_4, atm	C_5, atm			
0.11	0.30	0.49	0.04	0.06	1	4100	3840 to 4380
.8	3.1	4.7	.6	.9	10	4540	4220 to 4890
6	31	42	8	13	100	5070	4650 to 5540
42	292	361	120	185	1000	5740	5150 to 6400

(b) Relative concentrations of carbon vapor species above graphite at 4000^{o} K

Reference	Carbon molecular species											
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{14}
6	22.2	62.5	100.0	7.8	11.1	-----	----	----	----	----	----	-----
7	37.0	31.4	100.0	2.13	7.9	0.413	1.11	0.19	0.11	0.32	0.15	0.042

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(c) Cerium

Vapor pressure, atm	Extrapolated temperature, ^{o}K	Temperature uncertainty, ^{o}K
1	3560	3480 to 3680
10	4200	4080 to 4430
100	5160	4940 to 5560
1000	6670	6250 to 7460

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(d) Data for molybdenum from reference 9

Vapor pressure, atm	Extrapolated temperature, ^{o}K	Temperature uncertainty, ^{o}K
1	5 100	4880 to 5 350
10	6 100	5740 to 6 510
100	7 590	6980 to 8 320
1000	10 040	8900 to 11 530

(e) Data for molybdenum from reference 10

1	4 700	4590 to 5 090
10	5 480	5310 to 6 090
100	6 570	6290 to 7 580
1000	8 180	7720 to 10 040

(f) Data for molybdenum from reference 11

1	4 640	4500 to 4 830
10	5 340	5180 to 5 690
100	6 440	6110 to 6 910
1000	7 980	7430 to 8 810

(g) Data for molybdenum, combined data of references 9, 10, and 11

1	4 800	4500 to 5 350
10	5 630	5180 to 6 510
100	6 820	6110 to 8 320
1000	8 620	7430 to 11 530

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(h) Data for niobium from reference 12

Vapor pressure, atm	Extrapolated temperature, ^{o}K	Temperature uncertainty, ^{o}K
1	4520	4360 to 4800
10	5090	4870 to 5500
100	5830	5510 to 6440
1000	6830	6340 to 7780

(i) Data for niobium from reference 13

1	4760	4520 to 5040
10	5430	5080 to 5840
100	6300	5800 to 6950
1000	7530	6750 to 8580

(j) Data for niobium, combined data of references 12 and 13

1	4660	4360 to 5040
10	5280	4870 to 5840
100	6100	5510 to 6950
1000	7220	6340 to 8580

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(k) Platinum

Vapor pressure, atm	Extrapolated temperature, ^{o}K	Temperature uncertainty, ^{o}K
1	4070	3640 to 4 740
10	4780	4130 to 5 880
100	5790	4760 to 7 760
1000	7330	5620 to 11 400

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(l) Data for ruthenium from reference 16

Vapor pressure, atm	Extrapolated temperature, ^{o}K	Temperature uncertainty, ^{o}K
1	4280	3960 to 4620
10	4930	4450 to 5440
100	5790	5070 to 6610
1000	7040	5900 to 8430

(m) Date for ruthenium from reference 17

1	4080	3870 to 4230
10	4650	4340 to 4880
100	5410	4950 to 5770
1000	6470	5750 to 7050

(n) Data for ruthenium from reference 18

1	4370	4010 to 4710
10	5040	4520 to 5570
100	5960	5180 to 6800
1000	7280	6060 to 8730

(o) Data for ruthenium combined data of references 16, 17, and 18

1	4240	3870 to 4710
10	4870	4340 to 5570
100	5710	4950 to 6800
1000	6910	5750 to 8730

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(p) Tungsten

Vapor pressure, atm	Extrapolated temperature, ^{o}K	Temperature uncertainty, ^{o}K
1	5740	5620 to 5 930
10	6580	6420 to 6 880
100	7730	7470 to 8 180
1000	9340	8430 to 10 110

(q) Vanadium

1	3510	3420 to 3 640
10	4060	3920 to 4 260
100	4800	4590 to 5 120
1000	5880	5540 to 6 430

TABLE II. - Continued. EXTRAPOLATED VAPOR-PRESSURE DATA

(r) Yttrium

Vapor pressure, atm	Extrapolated temperature, ^{o}K	Temperature uncertainty, ^{o}K
1	3 480	3410 to 3 590
10	4 170	4050 to 4 390
100	5 210	5000 to 5 630
1000	6 950	6530 to 7 850

(s) Zirconium

1	4 840	4460 to 5 470
10	5 850	5240 to 6 970
100	7 410	6350 to 9 600
1000	10 100	8060 to 15 400

TABLE III. - CALCULATED CONSTANTS OF VAPOR PRESSURE EQUATION (EQ. (1))

Material	Constants		Material	Constants	
	A	D		A	D
Carbon (C_1)	-37 067	8.078	Molybdenum	-32 468	6.768
Carbon (C_2)	-42 798	9.924	Niobium	-39 308	8.444
Carbon (C_3)	-41 115	9.720	Platinum	-27 546	6.747
Carbon (C_4)	-50 165	10.818	Ruthenium	-32 927	7.766
Carbon (C_5)	-50 820	11.132	Tungsten	-44 680	7.790
Cerium	-22 816	6.419	Vanadium	-26 134	7.441
			Yttrium	-20 821	6.001
			Zirconium	-27 866	5.758

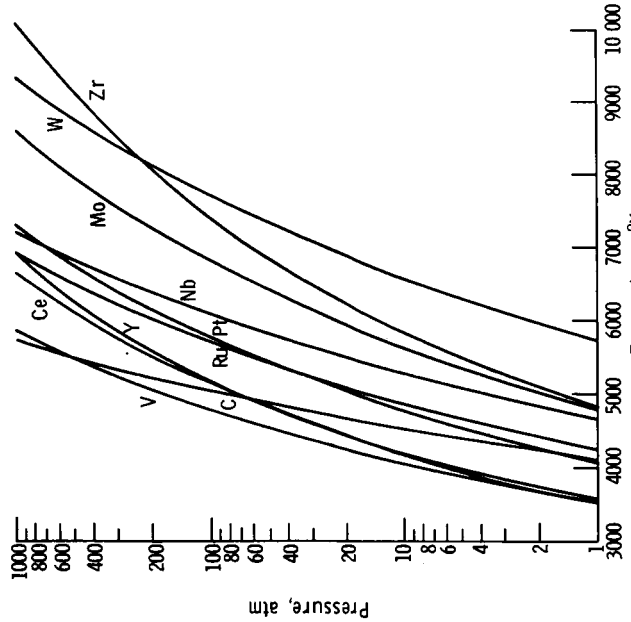

Figure 2. - Extrapolated vapor-pressure data to 1000 atmospheres.

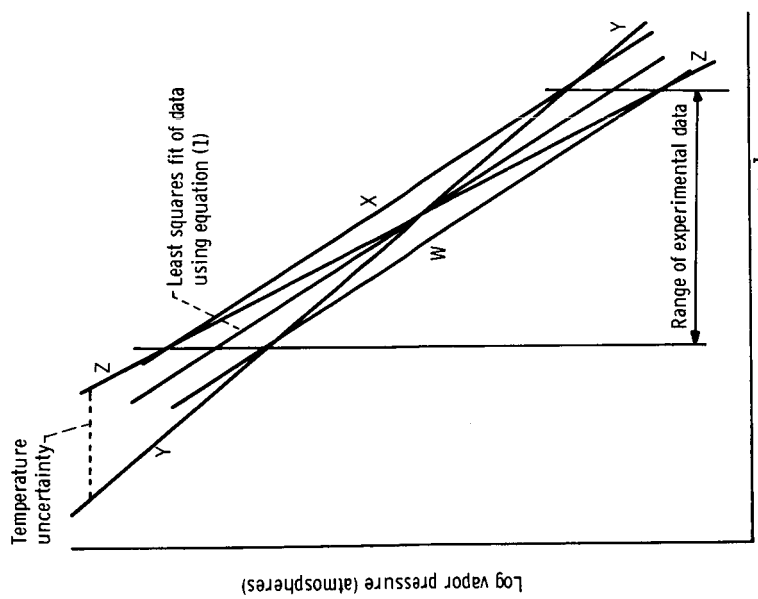

Figure 1. - Schematic drawing of visual error analysis.